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AD NUMBER
AD385867
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FROM: confidential
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Technical Report S-154

HYBRID MOTOR CONCEPTS III. STATIC TESTING OF BLADDER AND PISTON EXPULSION SYSTEMS FOR A TANDEM SOLID-HYBRID MOTOR (U)

by

W. C. Stone

November 1967

U. S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

Contract DA-01-021 AMC-15365(Z)

ROHM AND HAAS COMPANY
REDSTONE RESEARCH LABORATORIES
HUNTSVILLE, ALABAMA 35807

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(U) FOREWORD

The work described in this report was performed under Contract DA 01-021 AMC-15365(Z) for exploratory development of hybrid propulsion technology for missiles and rockets under the cognizance of Propulsion Systems Engineering Branch, Army Propulsion Laboratory and Center, Research and Development Directorate, U. S. Army Missile Command. This report, together with Rohm and Haas Report S-82 (August 1966), constitutes the final report on this contract.

Grateful acknowledgement is made to Mr. James C. Hodges of Propulsion Systems Engineering Branch for the effective technical liaison provided during this program.

(U) ABSTRACT

A hybrid propulsion system consisting of a five-inch solid–hybrid motor, a bladder expulsion tank and valves, and controls was evaluated in fourteen static tests and one flight test. Four static tests proved the satisfactory operation of the hybrid motor (developed in a previous program) when supplied with inhibited red fuming nitric acid by the bladder expulsion tank, pressure regulator, and nitrogen storage tank. Six motors were static tested to determine the effect of conditioning temperature on hybrid-motor operation. Although the hybrid-fuel regression rate decreased, the oxidizer rate increased with decreasing temperature, resulting in little overall change in the chamber pressure.

A control system based on the linear relationship between the integral of pressure over time and the propellant expelled from a rocket motor was evaluated with the low- and high-temperature firings. The system worked well in sequencing the operation of the hybrid motor to follow the solid-booster operation by measuring $\int Pdt$ for the booster.

One solid–hybrid motor was successfully flight tested on March 23, 1967. Operation of the motor consisted of one second of solid boost followed by two seconds of hybrid sustainer thrust. Motor performance was very similar to that of static test motors.

A gas-generator-pressurized piston expulsion system was developed and tested at -40°, 77°, and 140°F. The gas-generator propellant charge was mounted on the piston, inside the tank which it pressurized. All parts of the system performed satisfactorily except the hot-gas relief valve, whose operation was erratic.

(U) CONTENTS

Section I. (U) INTRODUCTION

One of the primary requirements for an artillery rocket is the ability to engage both long- and short-range targets. When solid-propellant rocket motors are used for propulsion, zoning is obtained by varying the launch angle or terminating the motor thrust by releasing the nozzle or opening head-end ports. For short ranges the first method can result in large wind-drift errors during the long flight times resulting from high quadrant elevations; the second method typically produces undesirable thrust peaks. A more desirable method of controlling range is to use a constant launch angle and a propulsion unit with thrust-termination capability.

The hybrid rocket motor can be cut off at any time and has a smooth thrust decay. Hence, the field-artillery rocket is a potential application for a hybrid motor. This propulsion unit would be of special use in small missiles if the total impulse of the motor could be controlled reproducibly by a timer or other simple device.

The Army Propulsion Laboratory and Center of the U. S. Army Missile Command has flight tested a vehicle to demonstrate range zoning using a hybrid motor. The Redstone Research Laboratories received a contract to manufacture and test the motor, and to check out the oxidizer expulsion system and controls which were provided by a second contractor. Initial design, feasibility testing, and development of the motor have been reported.[1,2]

To support the flight tests, the Redstone Research Laboratories conducted a static test program which consisted of the following tasks:

(a) Mate the hybrid motor with the bladder expulsion system and demonstrate satisfactory performance in four static tests.

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[1]Rohm and Haas Co., Huntsville, Alabama, HYBRID MOTOR CONCEPTS (I)—COMPONENT DEVELOPMENT AND REPRODUCIBILITY FIRINGS (U), W. C. Stone, 1 Sept. 1965, Report S-70, U. S. Army Missile Command, Redstone Arsenal, Alabama, Contract DA-01-021 AMC-11040(Z) (Confidential), AD-365 021.

[2]Rohm and Haas Co., Huntsville, Alabama, HYBRID MOTOR CONCEPTS (II)—DEVELOPMENT OF A TANDEM SOLID-HYBRID MOTOR FOR ZONING DEMONSTRATION (U), W. C. Stone, 2 Aug. 1966, Report S-82, U. S. Army Missile Command, Redstone Arsenal, Alabama, Contract DA-01-021 AMC-11040(Z) (Confidential), AD-374 398.

(b) Evaluate the performance of the integrating pressure-time control method for timing the start of the hybrid motor.

(c) Investigate the effect of temperature changes on hybrid motor operating pressure.

(d) Deliver seven motors for flight test and provide technical assistance in missile assembly and calibration of pressure gauges and control packages.

(e) Develop a gas-generator-driven piston expulsion system capable of operating from -40° to +140°F.

(f) Develop a short-burning-time booster motor to limit range of test vehicle.

This report describes the results of the test program.

Section II. (C) DESCRIPTION OF PROPULSION SYSTEM

1. (C) Description of the Tandem Solid-Hybrid Motor

(C) The tandem solid-hybrid motor (Figure 1) was a single-chamber dual-grain rocket motor. A twelve-point wagonwheel hybrid fuel grain was located in the forward case adjacent to the multiport injector-head. The fuel grain composition is shown in Table I.

Table I. (C) Hybrid Fuel Composition (RH-C-51) (U)

Ingredient	Weight Per Cent
CTPB Binder (ZL-434)[a]	71
Aluminum	10
Acryloid® [b] K-120	19

[a]Thiokol Chemical Corp., Trenton, N. J.
[b]Trademark of Rohm and Haas Co., Philadelphia, Pa.

(C) In the aft end of the motor, a slotted-tube solid-propellant grain was placed next to the exit nozzle. The propellant was a plastisol-nitrocellulose composition (Table II). The hybrid grain was separated from the solid propellant charge by an asbestos-phenolic mixer plate used to promote more efficient mixing of the hybrid combustion products.

Table II. (C) Composition of RH-P-112 Propellant (U)

Ingredient	Weight Per Cent
Double-base powder	16.67
Triethylene glycol dinitrate	37.33
Ammonium perchlorate	30.00
Aluminum	15.00
Resorcinol	1.00

(U) In operation, the solid propellant was ignited and burned out first. This propellant provided the minimum total impulse for launching and heated the hybrid fuel grain to ignition temperature. The volume vacated by the solid propellant gave a mixing chamber for the hybrid gases. Hybrid operation was timed to begin coincident with tail-off of the solid propellant. The inhibited red fuming nitric acid oxidizer (IRFNA) was sprayed down the valleys of the fuel grain by the

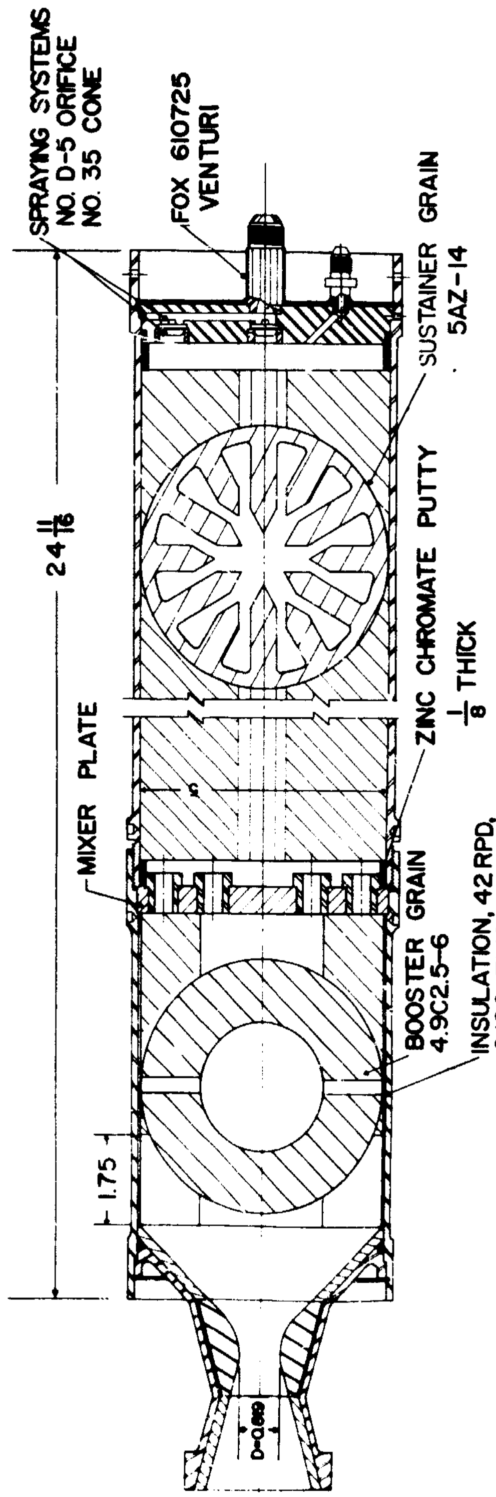

FIGURE 1. (U) TANDEM SOLID-HYBRID MOTOR

injector-head which had one injector for each grain valley and one for the center area. The oxidizer vaporized and mixed with gases from the decomposing fuel grain, and combustion was completed in the empty solid-propellant chamber. The motor was cut off by stopping the oxidizer flow, either by closing the valve or expending the supply.

(C) Typical performance parameters for the hybrid motor are shown in Table III; Figure 2 shows the thrust-time and pressure-time records. Further details on the motor development and testing may be found in Reference (2).

Table III. (C) Representative Performance Parameters of the Hybrid Flight Test Motor (U)

	Booster (Solid)	Sustainer (Hybrid)
Average thrust (lbf)	532	460
Average pressure (psia)	703	556
Burning time (sec)	1.90	7.25[a]
Propellant weight (lbm)	4.80	15.03[b]
Overall delivered specific impulse (lbf-sec/lbm)	230	

[a] Burning time = 7.25 sec when piston expulsion is used; t = 4.0 sec when bladder expulsion tank is used.
[b] Oxidizer weight = 12.32 lbm, expended fuel weight=2.71 lbm, o/f = 4.54 for piston expulsion tank.

2. (U) Description of Bladder Expulsion System

The expulsion and control system was made up of a control package, a nitrogen tank, a pressure regulator, an oxidizer tank with a stainless steel bladder, and an explosively actuated valve. Figure 3, a simplified cross-sectional drawing of the hybrid flight vehicle, shows the component layout of the hybrid propulsion system. A complete description of the vehicle is given in a final report on BEEPS.[3] The control package will be described in Paragraph 4. A spring-reference pressure regulator reduced the 3000 psia nitrogen pressure to 1250 psia for the oxidizer tank. Oxidizer was isolated in the spherical storage tank by a stainless steel hemispherical bladder. During expulsion, the bladder inverted to expel about 95% of

[3]Hayes International Corp., Birmingham, Alabama, FINAL REPORT ON BEEPS, L. D. Schute and R. B. Phillips, 5 April 1967, Engineering Report No. 1407, (Unclassified), Contract DA-01-021 AMC-243(Z).

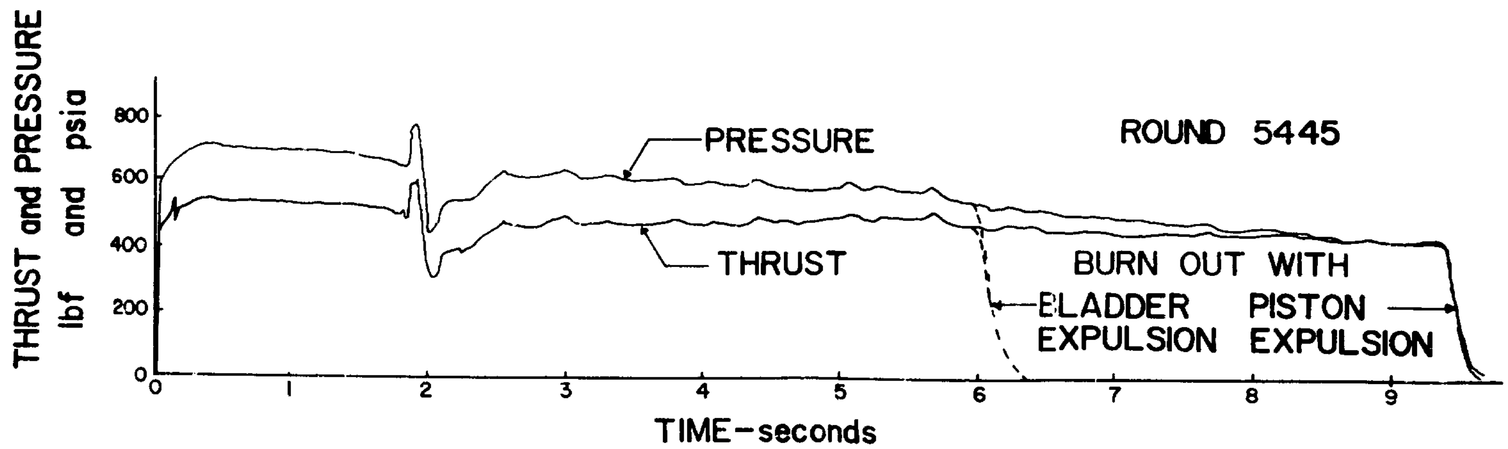

FIGURE 2. (U) PRESSURE AND THRUST HISTORIES FOR SOLID-HYBRID MOTOR

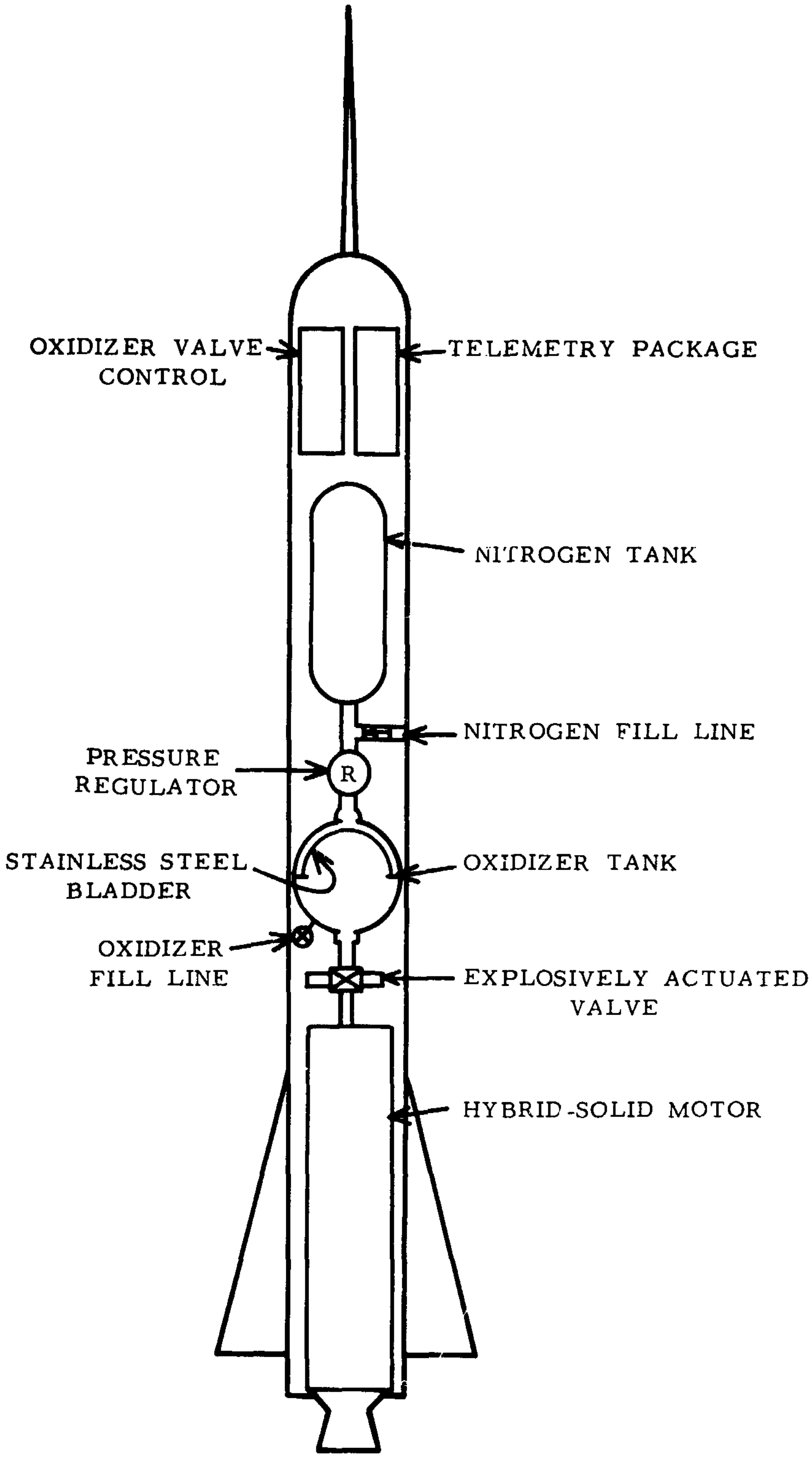

FIGURE 3. (U) HYBRID FLIGHT TEST VEHICLE SCHEMATIC

the 6.8 lb of IRFNA. The oxidizer valve was a balanced poppet design with the poppet moved by two explosive squibs. Initially, the valve was off. The poppet was moved to "on" by one squib, then to "off" again by the second squib. Flow control for the oxidizer was provided by a cavitating venturi which was welded into the motor head (Figure 1).

3. (U) Assembly and Filling Procedures

The hybrid propulsion system assembly began with the loading of the solid-hybrid motor. Next, the loaded motor, which included a live solid-propellant grain, igniter, and inert hybrid fuel grain, was attached to the oxidizer expulsion system. The entire expulsion system was elevated to 45° for filling of the oxidizer tank by pressure feeding. The system was then lowered to the firing position for connecting of the pressure gauges and electrical controls. For static testing of the propulsion system, an external thrust frame was attached to take the motor thrust. The thrust frame and propulsion system are shown in firing position in Figure 4.

Prior to firing, the nitrogen tank was pressurized to 3000 psia and the electrical control system was armed. These operations were carried out remotely because the oxidizer was pressurized as soon as the N_2 tank was filled and could enter the chamber if the valve leaked. Although the hybrid oxidizer and fuel present no hazard when mixed cold, the oxidizer will ignite the solid propellant after 3 to 5 minutes of contact. The electrical firing pulse to the motor also activates the valve control system which is described below.

4. (U) Description of the Oxidizer Valve Control System

The integral P-dt control method for rocket motors is based on the linear relationship between the propellant mass expelled through the nozzle and the area under the pressure–time curve. For a given propellant mass, the area under the pressure–time curve will be constant and independent of motor temperature or operating pressure. (The Appendix presents a derivation of this relationship.) Hence, this method can be used to measure the burnout time of the solid propellant in the solid-hybrid motor and therefore time the opening of the oxidizer valve. By proper calibration, the hybrid operation can be timed to start immediately at the end of solid burning, thereby providing a continuous pressure and thrust history. This type of control has two distinct advantages: (a) it will correct for changes in burning time resulting from temperature changes, and (b) it can be used to control total impulse of the motor.

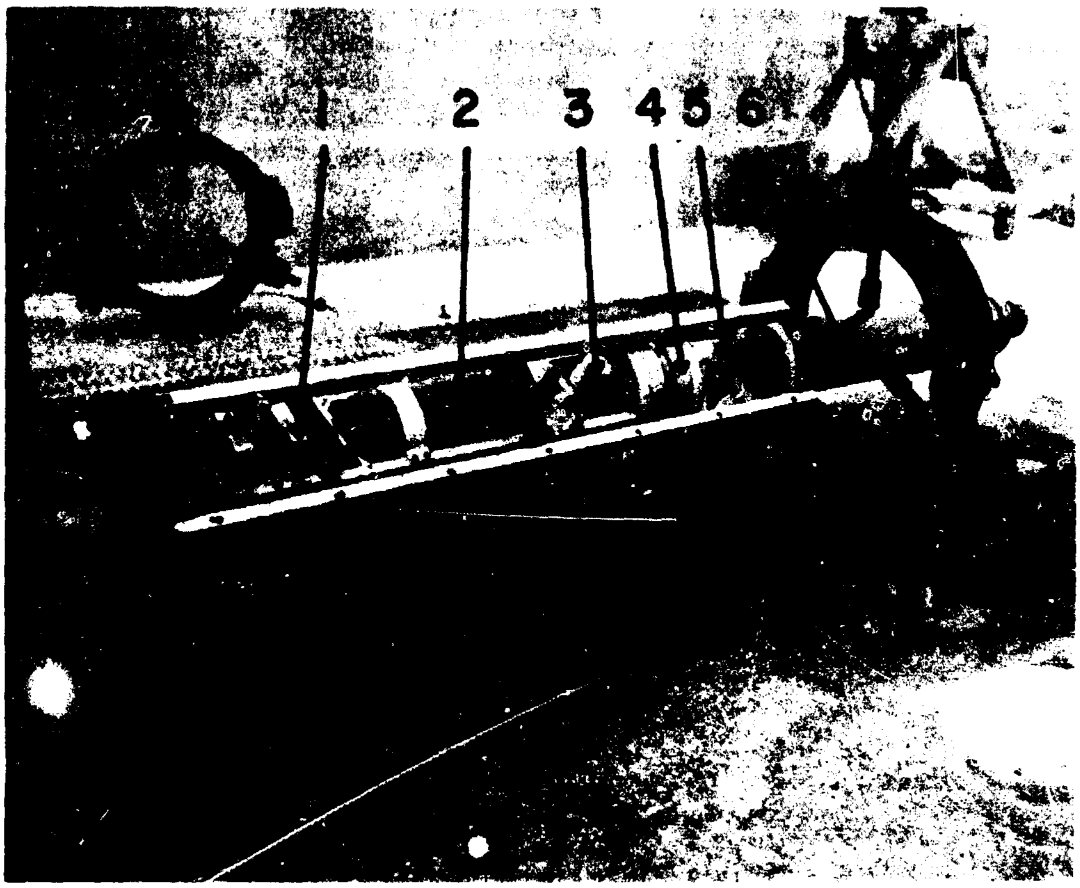

FIGURE 4. (U) SOLID-HYBRID PROPULSION SYSTEM AND THRUST FRAME

1. Integrator Control Package
2. Nitrogen Tank
3. Pressure Regulator
4. Oxidizer Tank
5. Squib Operated Valve
6. Hybrid Motor

(U) The integral P-dt control package for the hybrid propulsion system was built by Hayes International Corporation and is described in Reference (3). Briefly, the control consisted of a potentiometer-type pressure gauge[4] whose output voltage charged a capacitor. When the capacitor charge reached a preset voltage level, a silicon-controlled rectifier conducted energy from a bank of charged capacitors to the on squib of the oxidizer valve. This same signal started a timer (also based on capacitor charging) which switched energy from a second bank of capacitors to the off squib of the oxidizer valve.

(U) A schematic of the pressure integrator control is shown in Figure 5. The integrator control had its own internal battery which provided a reference voltage and input voltage to the potentiometer pressure gauge. Figure 4 shows the "black box" containing the integrator, battery, and capacitors.

[4]Type 461319-A1V6-100-50, Giannini Controls Corp., Duarte, Calif.

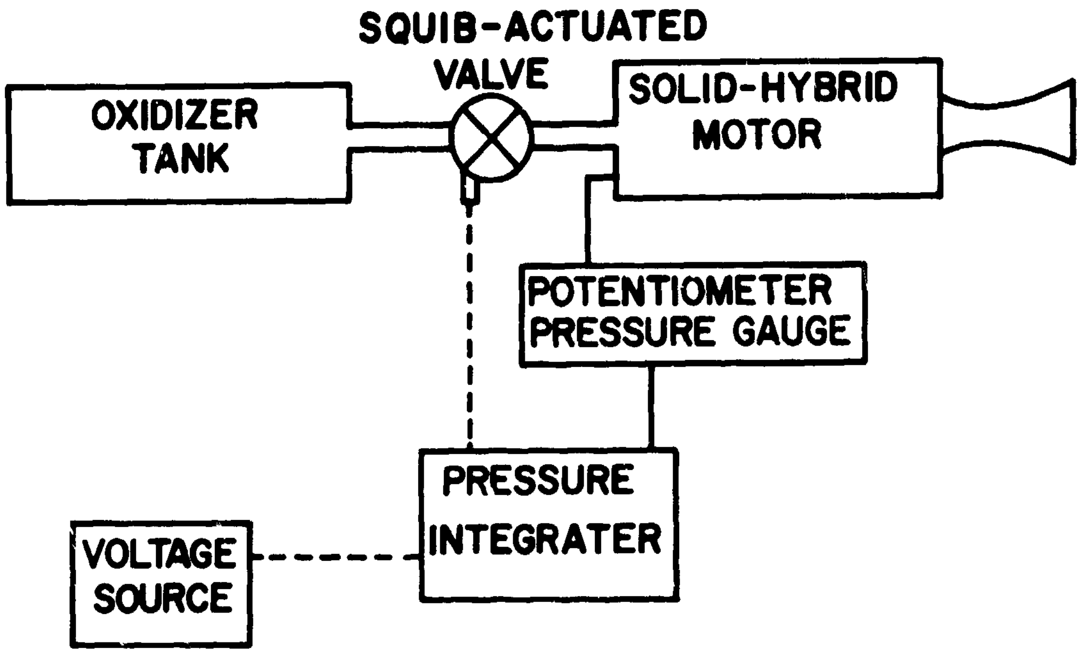

FIGURE 5. (U) SCHEMATIC OF PRESSURE INTEGRATOR CONTROL

Section III. (C) RESULTS OF STATIC TESTS

1. (U) Calibration Procedure

The integrator control package was calibrated by comparing it with a similar digital integrating system which was used in actual motor firings. In the calibration set-up (Figure 6), 600-psia nitrogen was fed to the pressure gauges of both systems. The time required to reach the set integral of P-dt for each system was printed on an oscillograph record. Successive adjustments were made until the control package output matched the output of the digital system.

In reproducibility tests of the integrator control package, the unit printed out within ±5 msec of the digital system when both were run at 600 psia. The run times were about two seconds—the burning time of the solid booster. When the pressure was changed from 600 psia, the integrator errored—by as much as 50 msec in a two-second run at 400 psia. This error was not sufficient to cause operational. problems with the hybrid motor, however. The cause of the error was not found, although it was thought to be non-linearity in the potentiometer pressure gauge.

All integrator control packages used in the program—for both flight test and static test—were calibrated by this procedure.

2. (C) Demonstration of Bladder and Motor Performance

Both hybrid motor and expulsion system were tested in previous programs—the hybrid motor at Rohm and Haas and the bladder expulsion system at Army Propulsion Laboratory and Center. The first four static tests were run to prove the satisfactory mating of the two systems into a propulsion unit. These tests were very successful and consistent values of pressure and thrust were obtained (Table IV). All components performed satisfactorily during these tests after a problem in squib wiring was discovered and corrected. Representative pressure and thrust data are shown in Figure 2. Figure 7 shows a diagram of pressure levels within the system.

3. (C) Effect of Temperature on Hybrid Operation

(U) Four motors were fired to study the effect of temperature on the hybrid propulsion system. For these tests, the propulsion system was enclosed in an insulated box and conditioned for six hours prior to firing. The conditioning box was a temporary

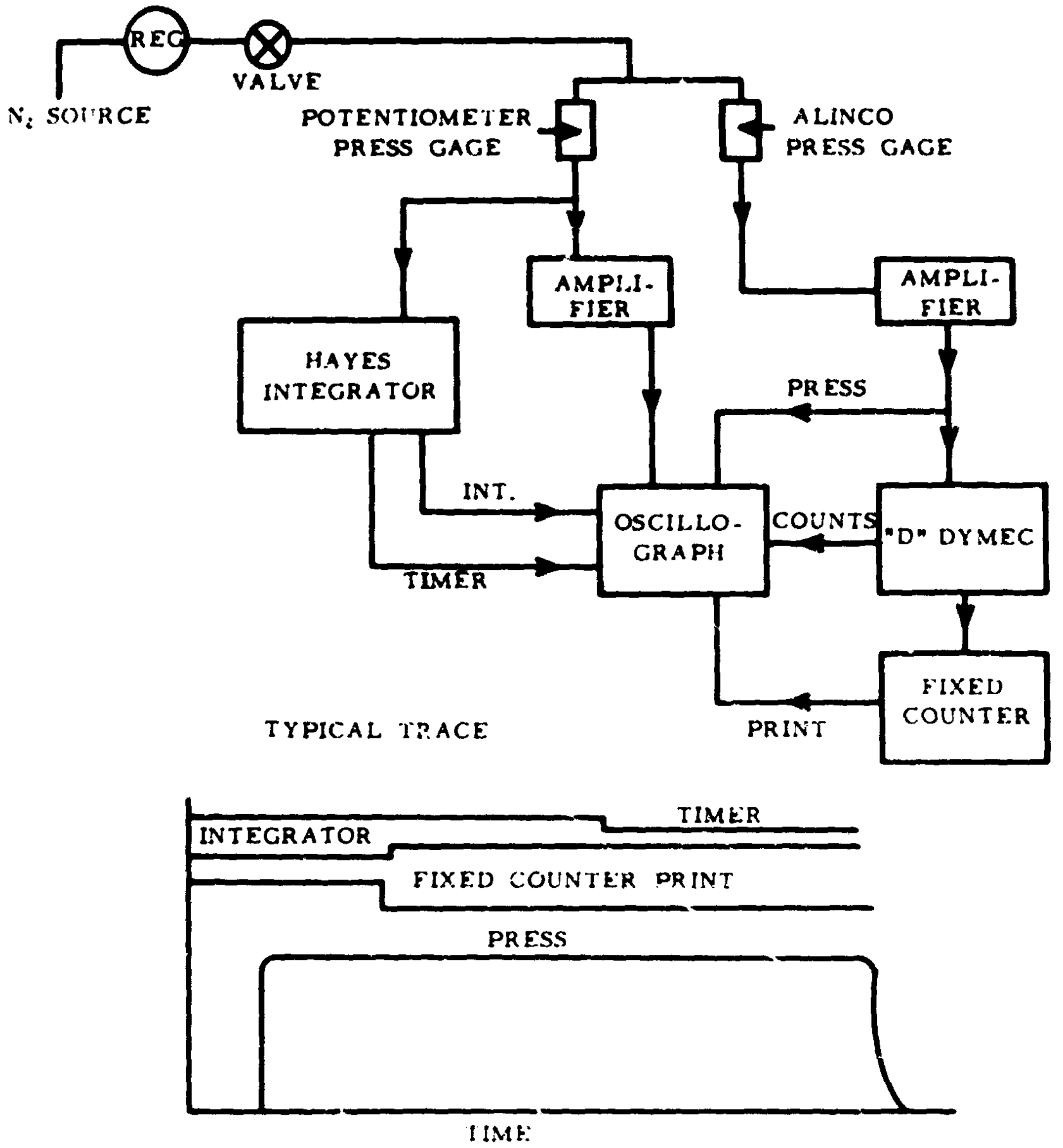

FIGURE 6. (U) SCHEMATIC OF INTEGRATOR CALIBRATION SET-UP

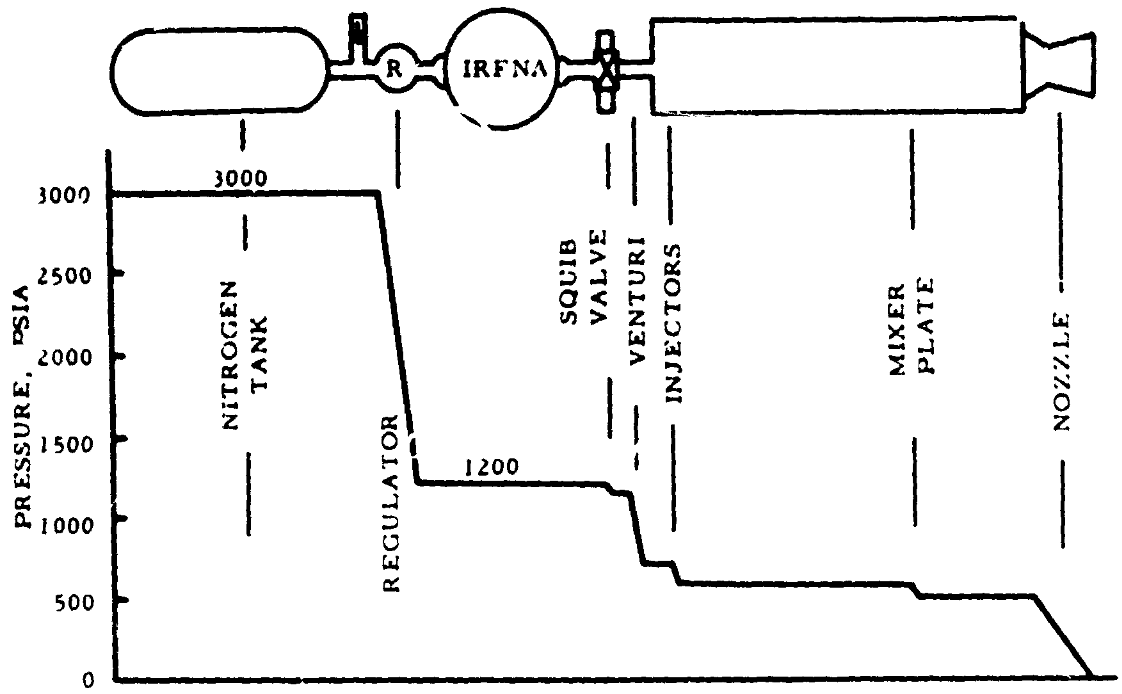

FIGURE 7. (U) PRESSURE LEVELS WITHIN THE PROPULSION SYSTEM

Table IV. (C) Ballistic Data from Hybrid Motors with Bladder Expulsion System (U)							
		Booster			Sustainer		
Round No.	Firing Temp. (°F)	Avg. Press. (psia)	Avg. Thrust (lbf)	Burn. Time (sec)	Avg. Press. (psia)	Avg. Thrust (lbf)	Burn. Time (sec)
7275	80	781	554	1.72	Sustainer did not fire because of faulty squib circuit		
7276	84	795	597	1.81	610	465	3.95
7314	74	752	538	1.80	605	434	2.25
7354	76	806	603	1.64	620	484	4.10

structure of sheet-insulating foam built to enclose the hybrid motor and expulsion system but not the integrator control. Cooling was accomplished by pumping from a dry ice - methylene chloride bath through heat transfer coils inside the insulation box. On 120°F shots, heated water was pumped through the coils. A circulating fan gave even temperature distribution.

(C) Performance of both expulsion system and motor was satisfactory at all temperatures. As expected, the solid-booster burning pressure varied considerably with motor temperature (Table V). The hybrid motor operating pressure did not vary significantly with temperature (Figure 8). Oxidizer pressure was higher at low temperatures because of the spring-reference design of the pressure regulator. Also, the IRFNA density changed with temperature, and this increased the flow rate through the venturi. While the oxidizer flow rate varied inversely with temperature, the fuel flow rate varied directly with temperature. The two effects were about equal in effect on chamber pressure which remained nearly constant (Table V). Between -31° and +120°F, the hybrid fuel regression rate exhibited a temperature sensitivity of σ_p = 0.28%/F°. It is evident from these tests that a hybrid motor can be designed to have zero temperature sensitivity.

4. (U) Evaluation of Integrator Control Performance

The integrator control for the oxidizer valve performed well in all but one test where the oxidizer valve did not open. Several other components could have prevented proper operation; nevertheless,

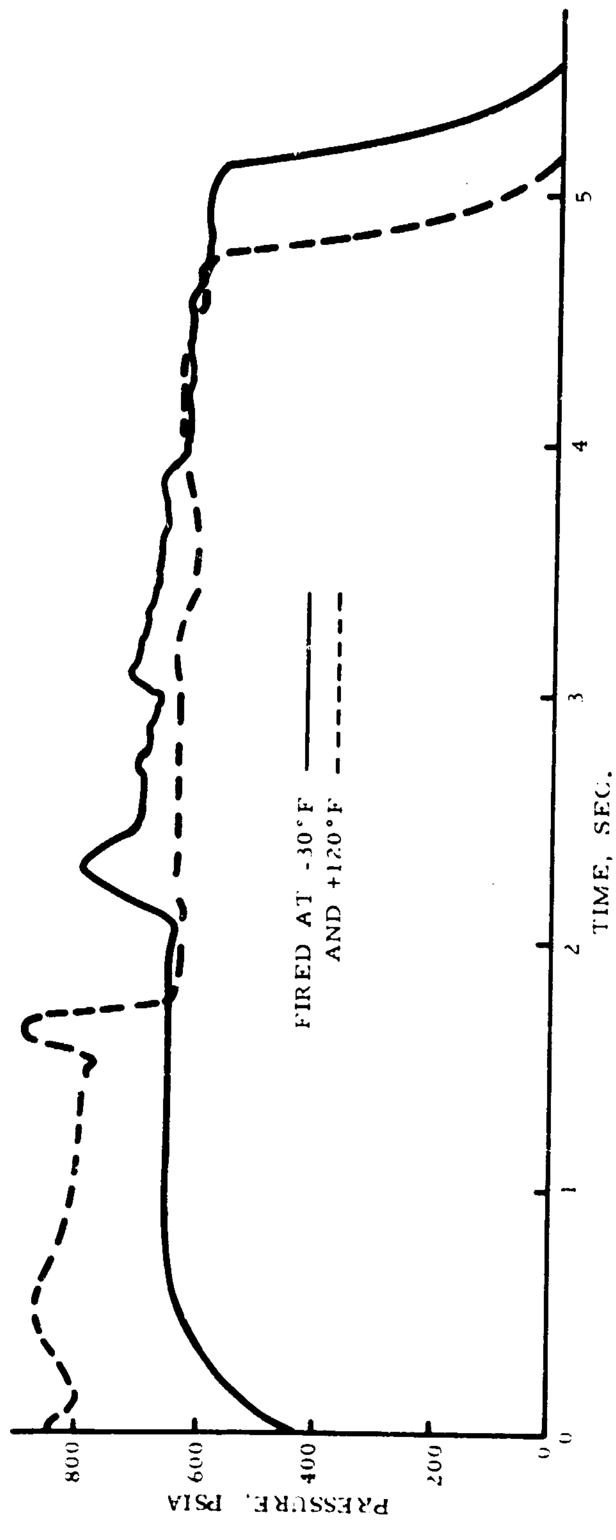

FIGURE 8. (U) PRESSURE HISTORIES FOR CONDITIONED MOTORS

Table V. (C) Effect of Temperature on Hybrid Motor Performance (U)

A. Booster Results

Round No.	Firing Temp. (°F)	Avg. Press. (psia)	Avg. Thrust (lbf)	Burn. Time (sec)
7950	-31	612	435	2.04
7992	-22	590	443	2.13
8210	120	823	654	1.52
8254	120	868	695	1.44

B. Sustainer Results

Round No.	Firing Temp. (°F)	Avg. Press. (psia)	Avg. Thrust (lbf)	Burn. Time (sec)	Oxidizer Press. (psia)	Oxidizer Flow Rate (lbm/sec)	Regression Rate (in/sec)
7950	-31	653	512	3.09	1264	1.83	0.013
7992	-22	619	479	3.02	1293	1.84	0.015
8210	120	645	504	3.09	1096	1.55	0.020
8254	120	649	506	3.12	1116	1.57	0.019

the integrator was suspect. Accurate timing was provided by the control on motors whose burning times varied from 1.44 to 2.13 seconds.

Although the control was not designed to operate over a wide temperature range, the unit operated satisfactorily over a 100°F temperature span. In the conditioned shots, the control box was not conditioned but was heated or cooled to some extent by conduction along the thrust harness (Figure 4). The control box temperature was estimated to be 100°F and 0°F, respectively on the high- and low-temperate shots.

5. (C) Tests of a Short-Burning-Time Booster

(U) The hybrid flight vehicle was limited to three seconds of powered flight to limit its maximum range. Since the principal interest in the flights was the hybrid motor operation, the solid burning time was cut to one second and two seconds of hybrid operation were allowed. To meet this requirement the solid-propellant grain was redesigned to give a one-second burning time. The slotted-tube grain was retained, but the web thickness was reduced from 1.5 to 0.75 inch. The new grain design (Figure 9) had a higher surface area

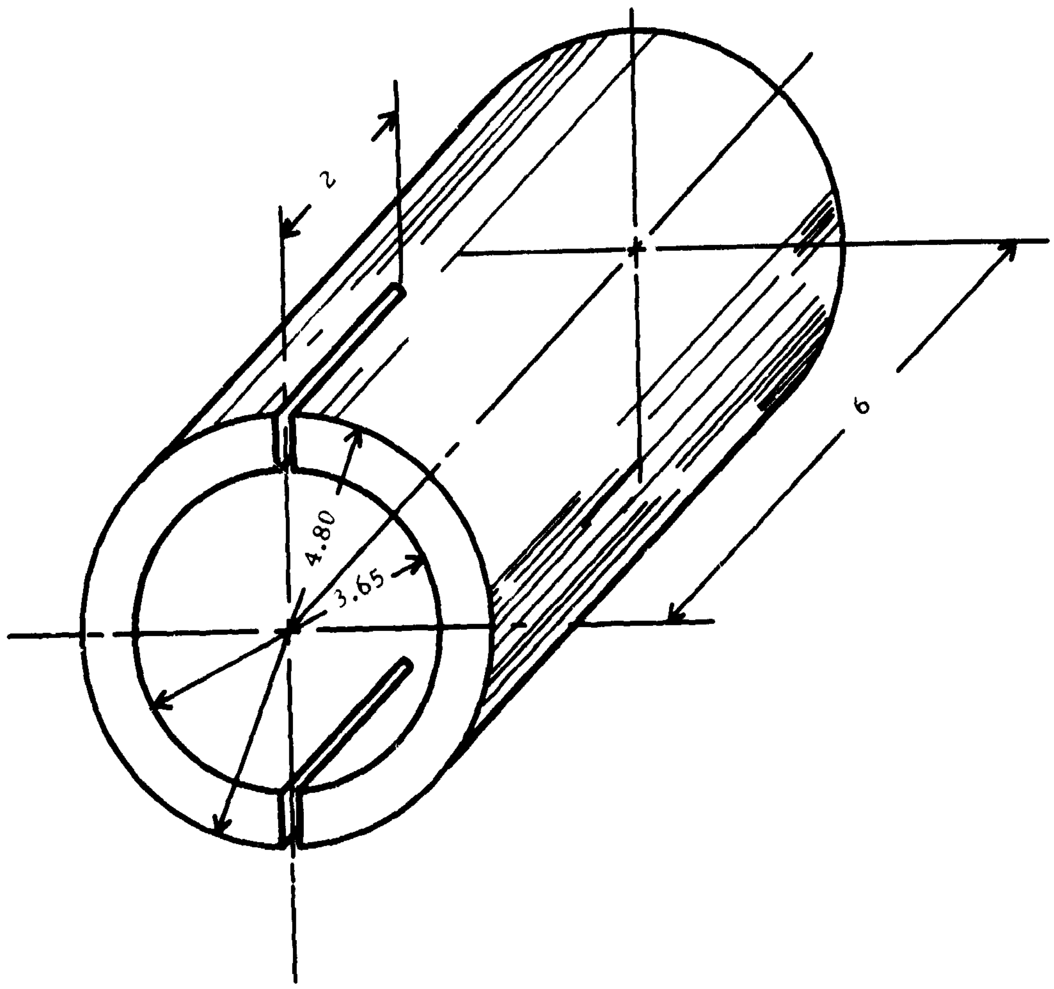

FIGURE 9. (U) THIN-WEB BOOSTER GRAIN

which resulted in a higher chamber pressure during solid burning. No other motor parameters were changed, but the integrator control was adjusted for the lower propellant weight.

(C) Two motors with the short-duration booster (burning time = one second) were made. The first motor was static tested and gave the desired results. The burning time was 1.01 seconds and the hybrid motor was properly ignited (Figure 10, Table VI). The second motor was successfully flight tested on March 23, 1967. Motor pressure and oxidizer pressure were to be telemetered, but the electronics failed and no data were obtained. Good photographic coverage of the flight showed that the motor performance was similar to that of static test motors.

Table VI. (C) Short-Burning-Booster Motor Data (Round 8001) (U)

	Booster (Solid)	Sustainer (Hybrid)
Average thrust (lbf)	560	484
Average pressure (psia)	736	619
Burning time (sec)	1.01	4.0
Propellant weight (lb) (consumed)	2.88	8.3

6. (C) Tests of Smokeless Hybrid Fuel

(C) Because of the recent interest in smokeless propellants, three hybrid motors were fired to determine the amount of smoke in the exhaust. These motors used RH-C-44, a propellant with 35% acrylic powder (Acryloid K-120) and 65% carboxyl-terminated polybutadiene binder. The IRFNA flow rate was reduced on two motors to give low-pressure sustainer operation. The third motor was fired to test high-pressure operation of the booster, which used a nonmetalized plastisol (RH-P-425) propellant.

(C) On Round 7906, the hybrid grain did not ignite because the oxidizer injection was not started until after booster burnout. On the third firing the hybrid burned at 223 psia for 21 seconds (Table VII). The exhaust was very smoky, probably due to carbon which was not burned at the low operating pressure. Hence, the propellant combination produced a smoky exhaust when burned at low pressure. This same motor and propellant produced a clean exhaust at 600 psia.

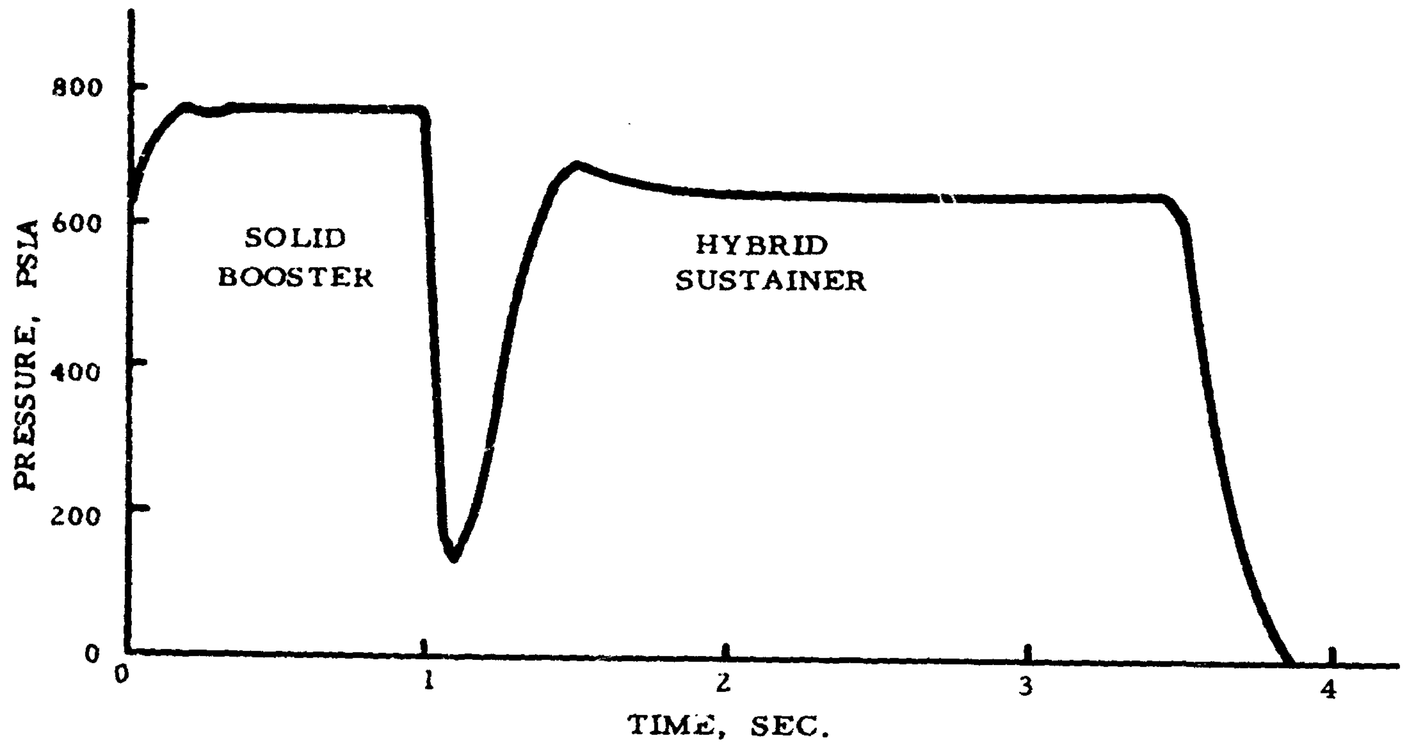

FIGURE 10. (U) PRESSURE HISTORY FOR THIN-WEB BOOSTER MOTOR

Table VI. (C) Ballistic Data on Smokeless Hybrid Firings (U)

Round No.	Booster Avg. Press. (psia)	Booster Burn. Time (sec)	Sustainer Avg. Press. (psia)	Sustainer Burn. Time (sec)
7859	1656	0.79	Smokeless booster only.	
7906	1515	0.80	Sustainer did not ignite because of late oxidizer entry.	
7951	1597	0.80	223	21.0

Section IV. (C) HYBRID MOTORS FOR FLIGHT TESTS

1. (C) Motors Delivered for Flight Tests

(U) Five hybrid motors were delivered to Army Propulsion Laboratory and Center for testing. Two were static tested in the missile; three were flight tested. Four of the motors were the original configuration with the two-second booster; the fifth motor had a one-second booster. The motors differed only in propellant weight and burning time of the booster. Table VIII summarizes the motor propellant weights. The total weight of the loaded motors, including the injector head, was about 34.5 lb.

Table VIII. (C) Summary of Motor Propellant Weights for Delivered Motors (U)

No.	Solid (lb)	Oxidizer (lb)	Fuel[a] (expended) (lb)	Remarks
1	4.50	6.8	2.71	Static tested
2	4.50	6.8	2.71	Static tested
3	4.50	0	0	Inert hybrid section
4	4.50	6.8	0	Hybrid oxidizer valve did not open
5	2.80	3.4	1.36	1.0-second booster

[a]Total weight of the hybrid grain was about 5.9 lb.

2. (U) Performance of Motors

On the first static test, the hybrid motor did not burn, although the solid grain operated satisfactorily. Cause of the failure was not determined. The second static test was completely successful.

The first flight test of the hybrid flight vehicle used the two-second solid boost and a dummy hybrid section to test vehicle stability, which proved satisfactory. In the second flight, the motor was programmed to burn three seconds—two seconds of solid boost and one second of hybrid operation. The oxidizer valve did not open because of a controls failure.

On the third flight, the short-duration-booster motor was used. Since the total motor burning time was restricted to three seconds by range safety, the one-second booster allowed two seconds of hybrid operation. The flight test also had a simple timer to signal the oxidizer valve on and to start hybrid operation. The integrator and associated safety circuits were suspected as the cause of failure in the second flight test, and the integrator was replaced.

The vehicle was fired on March 23, 1967, and flew about 5000 feet down range. Average acceleration during powered flight was 5 g. Performance of the motor was estimated to be similar to the static test of the short-duration booster motor (Table VI) except that burning time of the sustainer was 2.0 seconds. Photographic coverage showed no adverse effects of the flight accelerations on the motor. Figure 11 shows the vehicle shortly after launch.

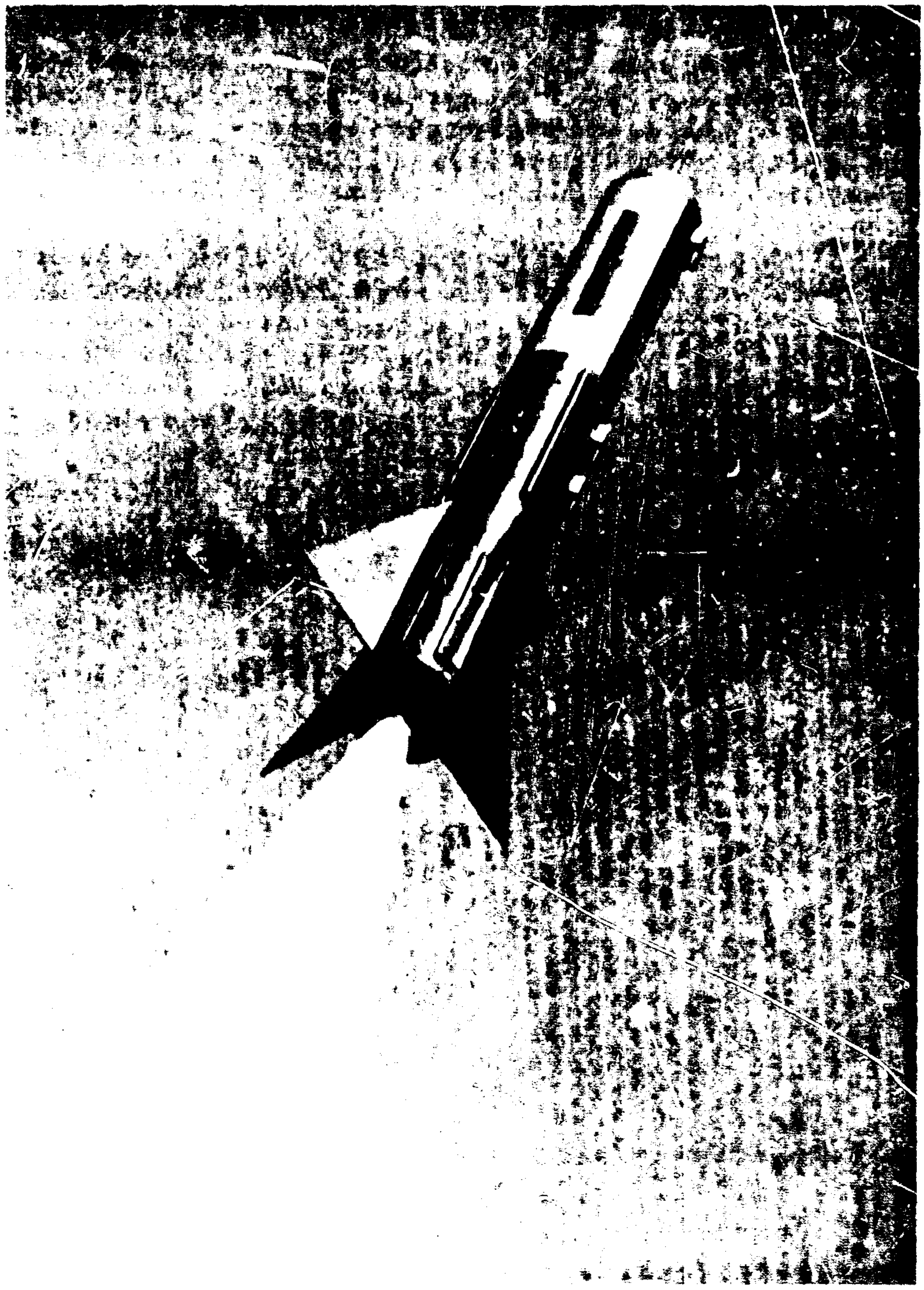

FIGURE 11. (U) HYBRID VEHICLE IN FLIGHT DURING BOOST PHASE

Section V. (C) PISTON EXPULSION SYSTEM TESTS

1. (U) Introduction

A gas-generator-pressurized piston expulsion system was developed during this program to serve as a back-up for the bladder expulsion system. An additional requirement for the piston system was operation at temperatures from -40 to +140°F. The piston system that was used in a previous program[5] was modified and used for this work. Dry nitrogen was used for pressurization in the earlier work and the system was operated at 80°F.

2. (U) Description of Hardware

Most gas generators are mounted outside the tank which they pressurize, and the hot gas exhausts through a sonic nozzle into the tank. This design is troublesome in small generators because the nozzle is often plugged by combustion products. In the system shown in Figure 12, the gas-generator charge was mounted directly on the piston in the chamber which it pressurized. The sonic nozzle was eliminated and the pressure was controlled by a hot-gas relief valve. A stainless steel rupture diaphragm, located in the oxidizer outlet line, was designed to break at 600 psia to allow separate handling of the filled tank without spillage. The stainless steel gas relief valve was a ball-seat, spring-reference design. Piston, tank, and end closures were made of aluminum.

Viton® [6] O-ring seals were used throughout and lasted six hours in IRFNA without deterioration. However, more permanent seals would be needed for longer times. The piston was coated with Teflon® [6] and insulated on the hot side with a phenolic-asbestos material.

3. (C) Sizing of the Gas Generator

Since the volume of gas generated depends on its final temperature which is controlled by heat loss to surrounding metal parts, several tests were required to fix the gas generator size. With the tank filled on the liquid side, a volume of 26 cubic inches remained on the hot side of the piston. An end-burning gas-generator charge 2 inches in diameter and 1.75 inches long provided adequate pressurization and expulsion. Approximately 0.3 pound of propellant was required to expel the 220 cubic inches of liquid.

[5] S-70, loc. cit.
[6] Trademarks of E. I. du Pont de Nemours & Co., Wilmington, Del.

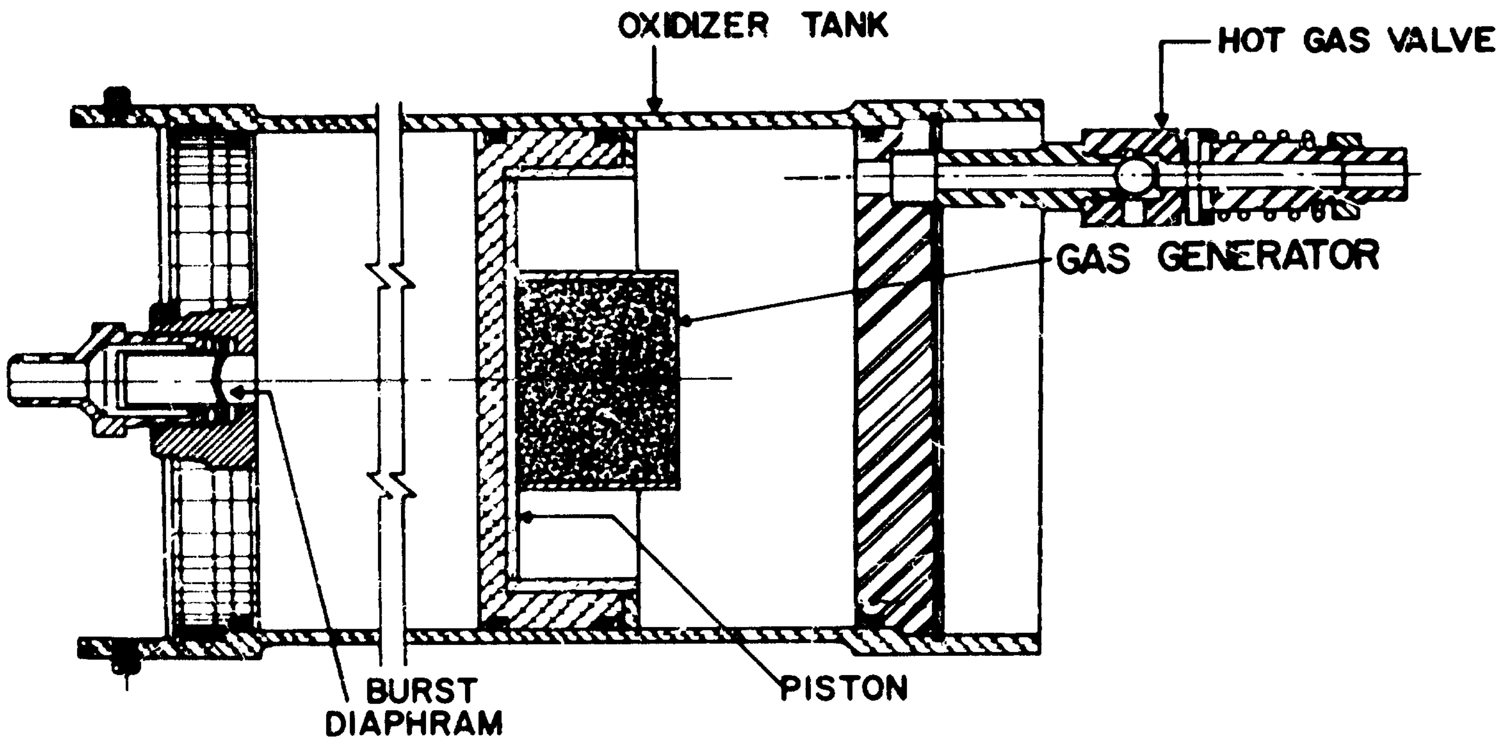

FIGURE 12. (U) DETAILS OF THE PISTON EXPULSION SYSTEM AND GAS GENERATOR

The sizing process was complicated by erratic operation of the gas relief valve. Close examination of this valve showed that the ball seat was contaminated by combustion products and leaked after the first opening. Although the valve was inadequate, another valve was not purchased or manufactured because of the time delays involved. Erratic operation of this valve did not prevent accomplishing the essential objectives of this portion of the program. Since the piston expulsion system had been proved previously for use with IRFNA, the conditioning tests were run using water and ethylene glycol. Table IX gives the composition of the gas-generator propellant.

Table IX. (C) Composition of RH-P-298 Propellant (Gas Generator) (U)

Ingredient	Weight Per Cent
Double-base powder	15.0
Triethylene glycol dinitrate	43.0
Oxamide	12.1
RDX	25.4
Lead Stearate	3.5
2 NDPA	1.0

4. (U) Results of Expulsion Tests

Six temperature conditioned tests were conducted; the gas generator and inert hardware worked well at -40°, 77°, and 140° F. The expulsion time as a function of pressure was affected little by temperature (Table X, Figure 13). Temperatures on the cylinder walls remained below 300° F even in the 140° F tests. Conduction to the cool liquid oxidizer and piston prevented overheating during the 5-second shot. No combustion instability was found and the propellant was easily ignited. One of the better pressure-time records is shown in Figure 14.

A typical operating sequence, as shown in Figure 14, began with pressurization by the igniter. The pressure was increased by the generated gas until the relief valve opened at about 1200 psia. Because the relief valve remained partilly open, the pressure slowly decayed, owing to the gas leak through the valve and the increased heat transfer as the tank walls were exposed.

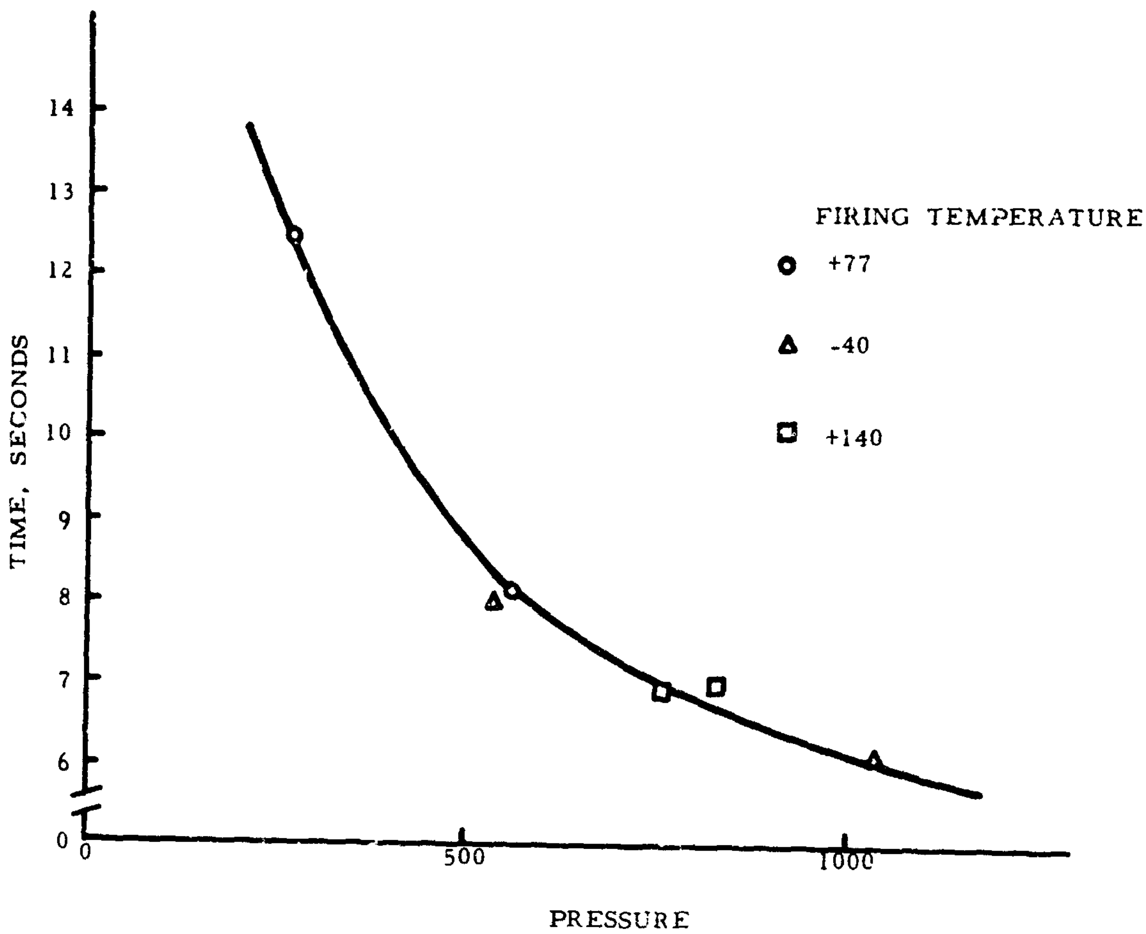

FIGURE 13. (U) EXPULSION TIME VERSUS TEMPERATURE

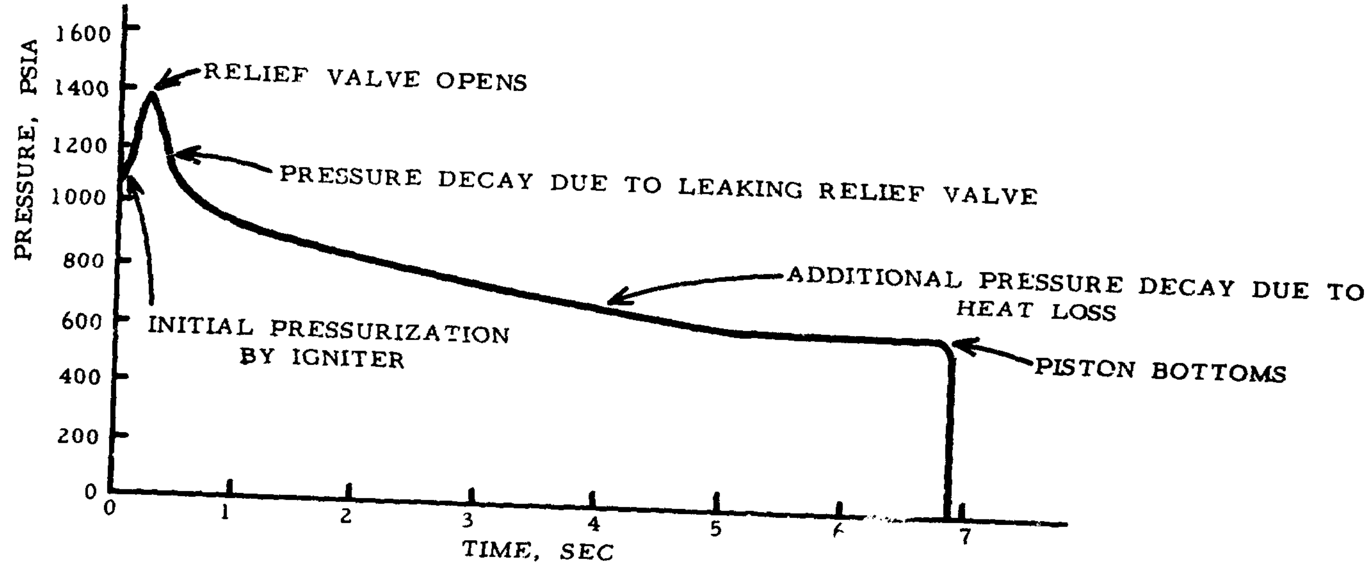

FIGURE 14. (U) PRESSURE HISTORY FOR PISTON EXPULSION SYSTEM

Round No.	Temp. (° F)	Avg. Pressure (psia)	Expelling Time (sec)
8743	-40	1039	6.07
8783	-40	540	8.00
8597	77	558	8.10
8729	77	268	12.47
8481	140	827	7.00
8593	140	759	6.80

Table X. (U) Conditioned Piston Expulsion System Firings

A properly functioning relief valve should produce a constant pressure. In this case, the gas-generator charge would be slightly oversize to accommodate the added heat loss near the end of the expulsion cycle. The excess gas would be dumped by the relief valve during the early portion of the expulsion cycle.

Section VI. (U) CONCLUSIONS

The hybrid propulsion system offers a practical method of thrust termination and total impulse control with smooth thrust decay at motor cut-off. The tandem solid-hybrid motor proved to be a reliable and reproducible propulsion system with total impulse variable from 1000 to 4350 lbf-sec. Efficient hybrid combustion and high specific impulse were obtained with the simple mixer plate followed by the empty solid propellant chamber.

The integral Pdt control method proved useful in timing motor cut-off or timing related events. However the system tested needs a better electronics design to improve reliability.

The tandem solid-hybrid motor works well with either the bladder or piston expulsion system supplying the oxidizer. Low- and high-temperature firings showed that the hybrid motor has a low π_K and may be designed to have zero π_K. The stainless steel bladder reversed uniformly without leaking to give steady expulsion in all tests.

The piston expulsion system worked well at temperatures of -40, +77, and +140°F. With the gas generator charge mounted on the expelling piston, the propellant was easily ignited and burned stably. Expulsion was smooth and leak-free.

In flight tests, an axial acceleration of five g's did not affect the performance of the hybrid motor.

(C) APPENDIX

RELATIONS OF MOTOR PROPELLANT WEIGHT AND PRESSURE VERSUS TIME INTEGRAL

(C) The experimental discharge coefficient for a rocket motor is obtained from

$$C_D = \frac{m_p}{(\int Pdt_a)(A_t)}$$

where C_D = discharge coefficient

$\int Pdt_a$ = action pressure integral

A_t = throat area

m_p = propellant mass

By rearrangement,

$$\int Pdt_a = \frac{m_p}{C_D A_t}$$

so that for a given propellant mass the pressure integral over the action time would be a function only of the discharge coefficient and the throat area.

(C) The discharge coefficient is affected by the initial grain temperature T_i as follows:

$$\frac{1}{C_D} = C \exp C'' (T_i - T_i^0)$$

where C and C" are constants and C" is very close to zero.[7]

C_D is therefore not a strong function of temperature and $\int Pdt_a$ should not be.

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[7]From "The Correlation of Interior Ballistic Data for Solid Propellants," by Geckler and Sprenger, Jet Propulsion 24, No. 1 quoted in Rocket Propulsion by Barrère et. al.

(C) Firing data for 2-inch motors containing a solid propellant were examined for the effect of temperature on C_D, $\int Pdt_a$, and $\int Pdt_b$. The pressure integrals were also divided by the propellant mass to determine whether reproducibility would be improved. The rounds were grouped according to temperature; averages for each temperature group and for the entire sample were obtained, and the standard deviations for the four $\int Pdt$ columns were also computed (Table XI).

(C) The data show no correlation of C_D or pressure integral with temperature. The standard deviation for $\int Pdt_a$ is less than that for $\int Pdt_b$, probably because of the method of determining burning time. The standard deviation for $\int Pdt_b$ is less than 2%, and all $\int Pdt_b$ values from this table are within 2σ of the mean. Dividing $\int Pdt$ by the propellant mass does reduce the standard deviation by about 30%, but sigma is not reduced below 1% by this normalization. Thus, the $\int Pdt$ is insensitive to temperature, and an integrating device may be used to control the start of hybrid operation.

Table XI. (U) Data on $\int Pdt$ versus Temperature							
Round	Temperature (°F)	Propellant Mass (lbm)	$\int Pdt_a$ psia-sec	$\int Pdt_b$ psia-sec	$\frac{\int Pdt_a}{m_p}$ $\frac{lbf\text{-}sec}{in^2/lbm}$	$\frac{\int Pdt_b}{m_p}$ $\frac{lbf\text{-}sec}{in^2/lbm}$	$C_D \times 10^3$ $\frac{lbm}{lbf\text{-}sec}$
4591	-42	0.32	183.9	180.6	574.7	564.4	6.15
4575	-42	0.32	186.6	176.7	583.1	552.2	6.12
4576	-42	0.32	185.6	175.6	580.0	548.8	6.12
4577	-42	0.32	184.4	179.5	576.3	560.9	6.14
4579	-42	0.33	189.8	183.0	575.2	554.5	6.10
Average			186.1	179.1	577.9	556.2	6.13
4570	8	0.34	193.1	189.4	567.9	557.1	6.11
4571	8	0.32	189.1	183.2	590.9	572.5	5.99
4572	8	0.33	190.7	185.6	577.9	562.4	6.09
4573	8	0.32	187.3	182.6	585.3	570.6	6.07
4574	8	0.33	190.8	187.7	578.2	568.8	6.05
Average			190.2	185.7	580.0	566.3	6.06
4586	52	0.32	186.4	183.4	582.5	573.1	6.07
4587	52	0.33	190.8	186.9	578.2	566.4	6.08
4588	52	0.33	186.8	183.1	566.1	554.8	6.10
4590	52	0.33	188.8	185.2	572.1	561.2	6.11
Average			188.2	184.7	574.7	563.9	6.09
4568	79	0.32	187.6	183.4	586.3	573.1	6.10
4569	79	0.33	190.2	185.6	576.4	562.4	6.09
Average			188.9	184.5	581.4	567.8	6.10
4592	96	0.33	188.3	183.2	570.6	555.2	6.10
4593	96	0.33	187.9	185.4	569.4	561.8	6.10
4595	96	0.33	186.0	180.3	563.6	546.4	6.08
4594	96	0.32	185.2	179.5	578.8	560.9	6.11
4596	96	0.32	182.8	176.4	571.3	551.3	6.10
Average			186.0	181.0	570.7	555.1	6.10
4597	144	0.33	188.8	184.3	572.1	558.5	6.12
4598	144	0.32	183.3	181.4	572.8	566.9	6.10
4600	144	0.33	191.3	183.9	579.7	557.3	6.15
4601	144	0.32	185.8	183.9	580.6	574.7	6.13
Average			187.3	183.3	576.3	564.4	6.13
Overall Average			187.7	182.8	576.4	561.4	6.10
Sigma			2.7	3.4	6.5	8.0	
% Sigma			1.4	1.9	1.1	1.4	

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Rohm and Haas Company Redstone Research Laboratories Huntsville, Alabama	2a. REPORT SECURITY CLASSIFICATION Confidential 2b. GROUP IV

3. REPORT TITLE

Hybrid Motor Concepts III. Static Testing of Bladder and Piston Expulsion Systems for a Tandem Solid-Hybrid Motor

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

William C. Stone

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
October 1967	35	0

8a. CONTRACT OR GRANT NO. DA-01-021 AMC-15365(Z) b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report S-154 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Initial distribution of this report has been made in accordance with contractual agreements. Qualified users may obtain from Defense Documentation Center.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Research and Development Directorate U. S. Army Missile Command Redstone Arsenal, Alabama 35809

13. ABSTRACT

A hybrid propulsion system consisting of a five-inch solid–hybrid motor, a bladder expulsion tank and valves, and controls was evaluated in fourteen static tests and one flight test. Four static tests proved the satisfactory operation of the hybrid motor (developed in a previous program) when supplied with inhibited red fuming nitric acid by the bladder expulsion tank, pressure regulator, and nitrogen storage tank. Six motors were static tested to determine the effect of conditioning temperature on hybrid-motor operation. Although the hybrid-fuel regression rate decreased, the oxidizer rate increased with decreasing temperature, resulting in little overall change in the chamber pressure.

A control system based on the linear relationship between the integral of pressure over time and the propellant expelled from a rocket motor was evaluated with the low- and high-temperature firings. The system worked well in sequencing the operation of the hybrid motor to follow the solid-booster operation by measuring the $\int P dt$ for the booster.

One solid–hybrid motor was successfully flight tested on March 23, 1967. Operation of the motor consisted of one second of solid boost followed by two seconds of hybrid sustainer thrust. Motor performance was very similar to that of static test motors.

A gas-generator-pressurized piston expulsion system was developed and tested at -40°, 77°, and 140°F. The gas-generator propellant charge was mounted on the piston, inside the tank which it pressurized. All parts of the system performed satisfactorily except the hot-gas relief valve, whose operation was erratic.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hybrid propulsion Temperature effects Impulse control Range zoning Gas generators Piston expulsion Bladder expulsion						